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WFIRST Low Order Wavefront Sensing and Control Testbed Performance Under Flight Like Photon Flux

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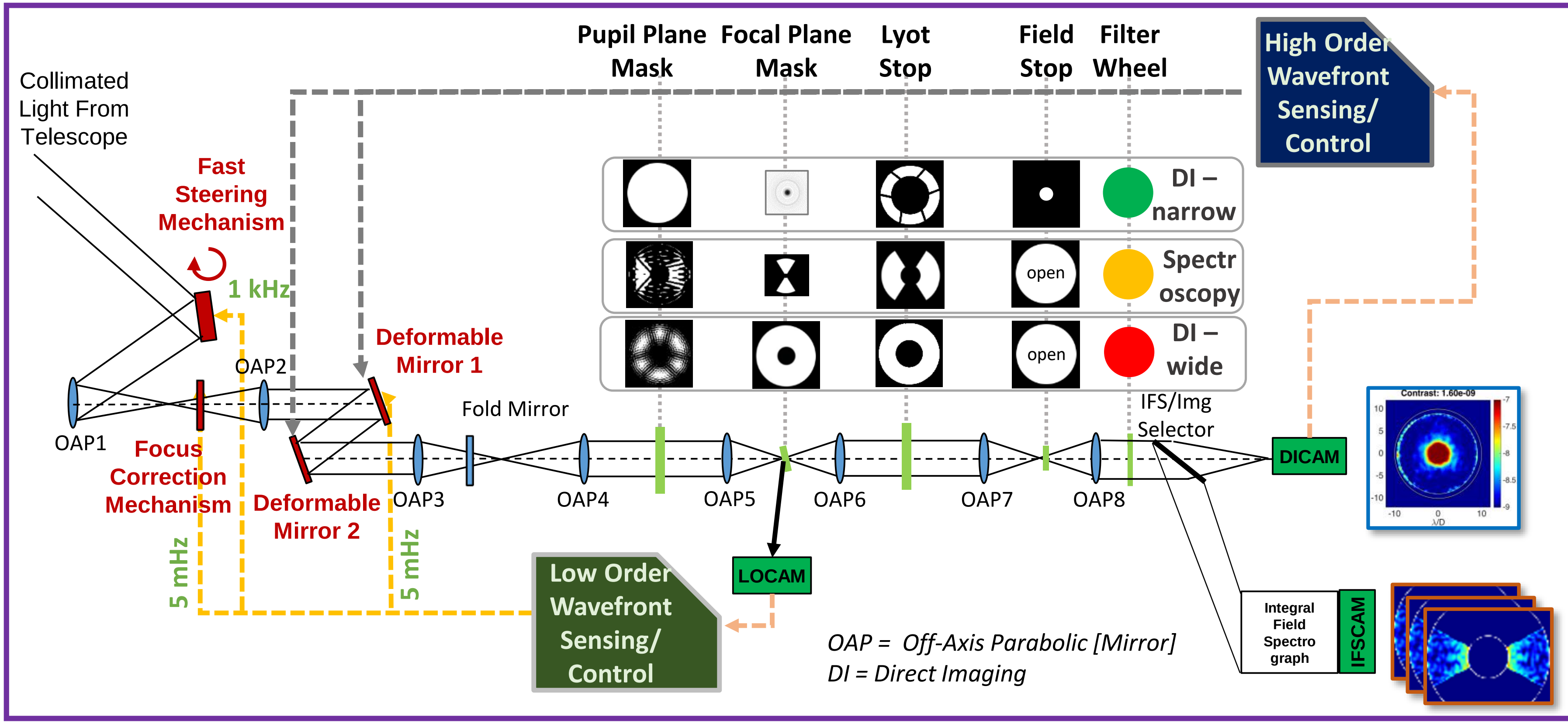
Outline

- Overview of Low order wavefront sensing and control (LOWFS/C) for WFIRST Coronagraph Instrument (CGI)
- Testing LOWFS/C at flight like photon flux
- LOWFS/C line-of-sight sensing and FSM control performance
- LOWFS/C focus sensing and DM correction performance
- Conclusion and future work

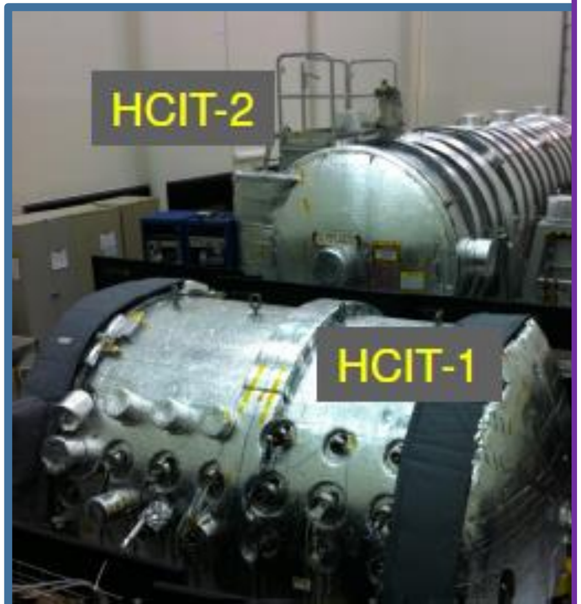
Companion paper:
10698-95: Hybrid Lyot coronagraph for WFIRST: high contrast testbed demonstration in flight-like environment, Byoung-Joon Seo, et al

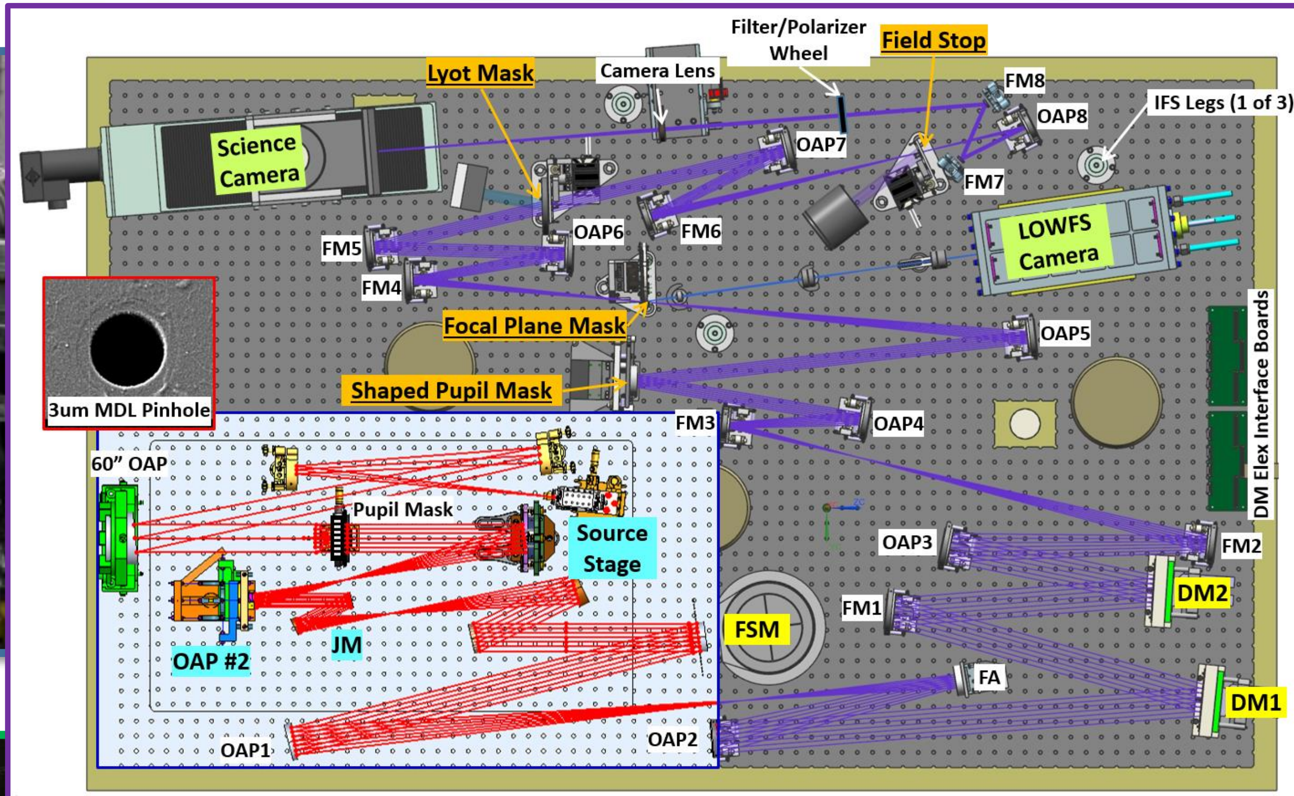
WFIRST CGI LOWFS/C Overview

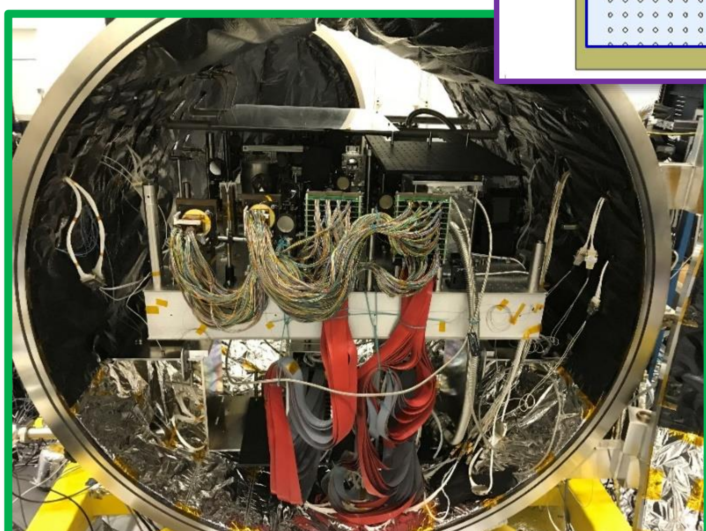


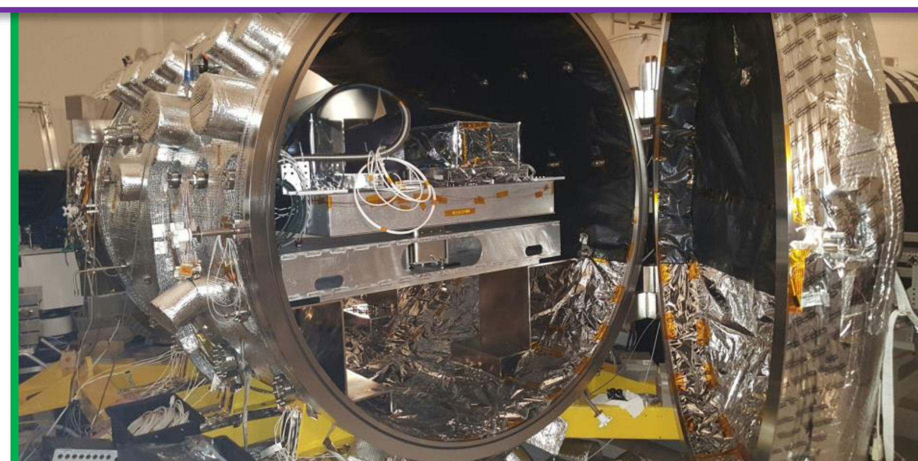
- LOWFS/C subsystem measures and controls line-of-sight (LoS) drift and jitter as well as the thermally induced low order wavefront drift. LOWFS sensor is Zernike wavefront sensor (ZWFS).
  - LoS: drift (< 2 Hz): ~14 mas, tonal jitter: ≤14 mas
  - WFE: drift (~10^{-3} Hz): ~0.5 nm (RMS), dominant by focus, astigmatisms and comas from the telescope optics rigid body motions
- Uses rejected starlight from occulter which reduces non-common path error
- LOWFS is a differential image wavefront sensor referenced to star light suppression wavefront control (HOWFS/C): it maintains wavefront established for high contrast

Occulting Mask Coronagraph (OMC) Dynamic Testbed







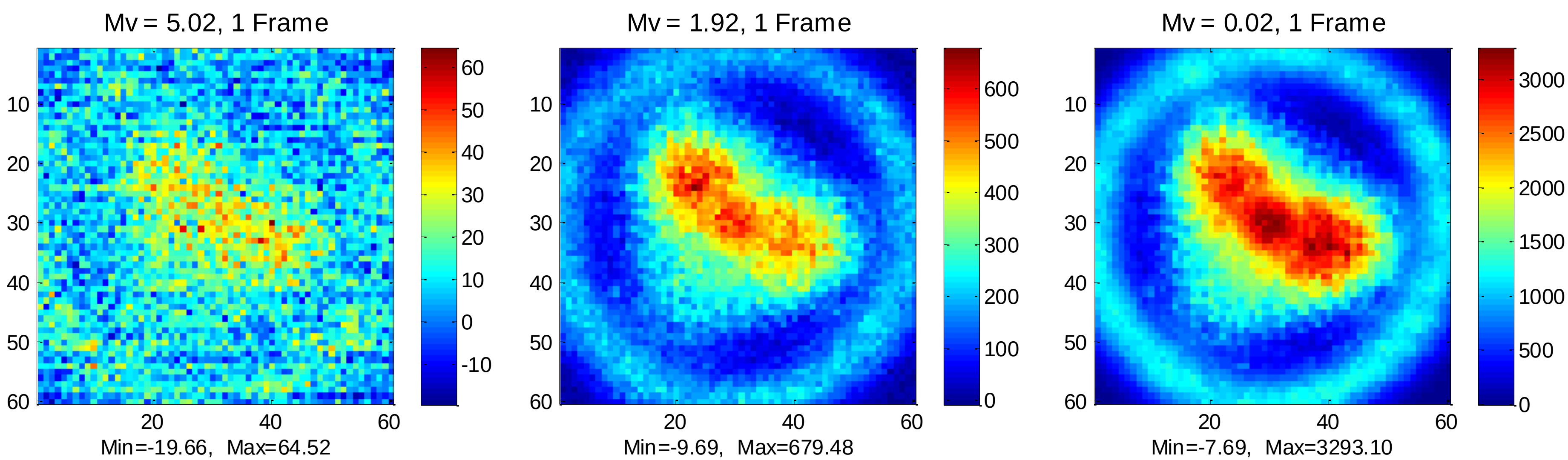


LOWFS/C Test with Flight Like Wavefront Disturbances

- **In our previous dynamics test (2017) we have demonstrated that LOWFS/C can maintain CGI contrast stability to better than 10^{-8} in presence of WFIRST like LoS and low order WFE disturbances in both SPC and HLC modes**
  - Three wavefront aberration modes demonstrated (tip-tilt and focus) are the dominant disturbances for WFIRST Coronagraph
  - LOWFS/C LoS control using the FSM and low order wavefront correction using a DM were demonstrated.
  - However, these tests were done on testbed using a bright source which has a brightness equivalent to a Mv = -3.5 star.
- **What will the LOWFS/C perform be under a realistic photon flux expected during the WFIRST CGI on-sky observation? The baseline WFIRST requirement for LOWFS/C on star brightness:**
  - Maintain the wavefront stability during CGI initial star light suppression wavefront control (EFC) on stars with brightness ***Mv ≤ 2.0***
  - Maintain the wavefront stability during CGI science target observations (no EFC) on stars with brightness ***Mv ≤ 5.0***
- LOWFS/C needs to perform under flight like photon flux

LOWFS/C Test with Flight Like Photon Flux and Disturbances

- Photon flux on the testbed LOWFS camera is measured and calibrated to equivalent total photoelectrons per frame for WFIRST LOWFS camera.
- Combination of ND filter and source power are used to reduce the photon flux on the LOWFS camera while fix source spectrum to the design bandwidth
  - LOWFS camera exposure time is fixed for the high speed read out
- Examples of a single frame image from testbed's LOWFS camera at equivalent stellar magnitude of Mv = 5 (left), Mv = 2 (middle), and Mv = 0 (right)
- **Fainter star image has lower image count (DN) and the photon noise is more pronounced**



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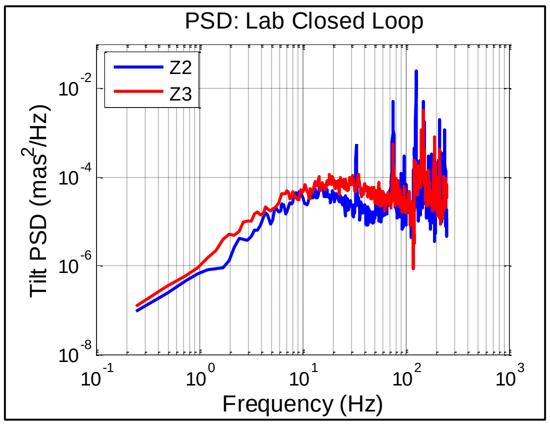
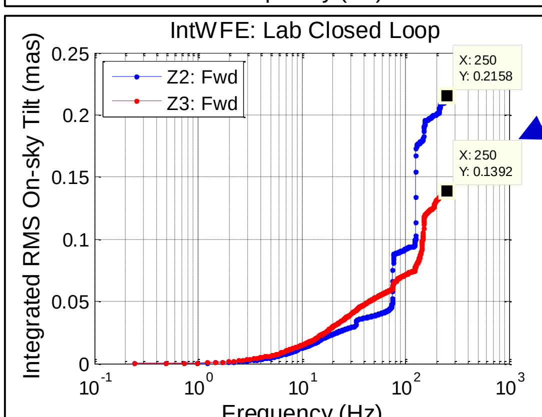
Compare Testbed Low Flux Sensing Error Against Sensor Model Prediction

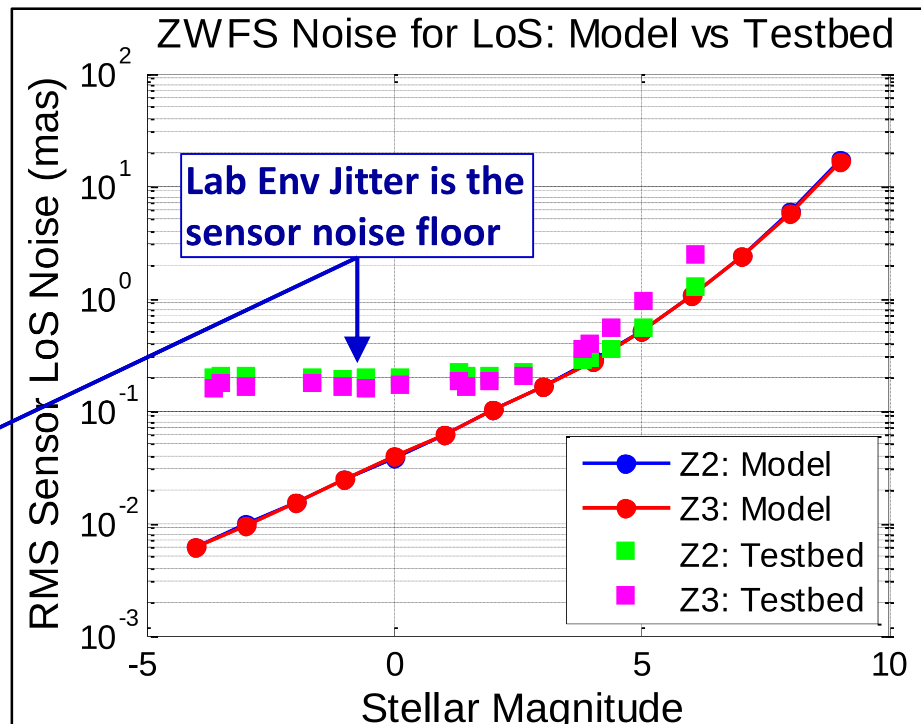
- **Testbed setup**
  - Under lab environment with FSM loop closed (PSD and integrated WFE plots on the left).
  - Testbed measurement includes the lab environment jitters: ~0.2 mas
  - Testbed CMOS camera read out noise is different in row and column directions, causing the difference of X and Y sensing noise.

- **LOWFS sensor model:**
  - Use testbed LOWFS camera image sampling
  - Including photon noise, read out noise, dark current
  - Model curve show that sensor error is dominated by photon noise for bright stars (Mv<3)

- ***Testbed data matches model prediction at low flux region, where sensor noise is dominated***
- ***At high flux region the measured error is limited by the lab environment jitter***







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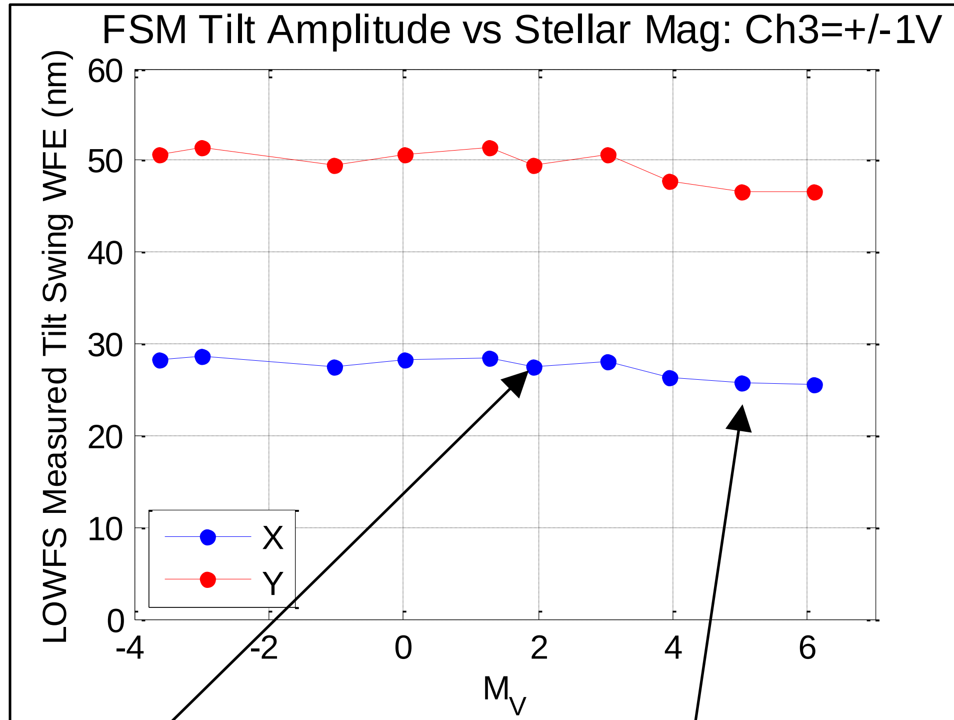
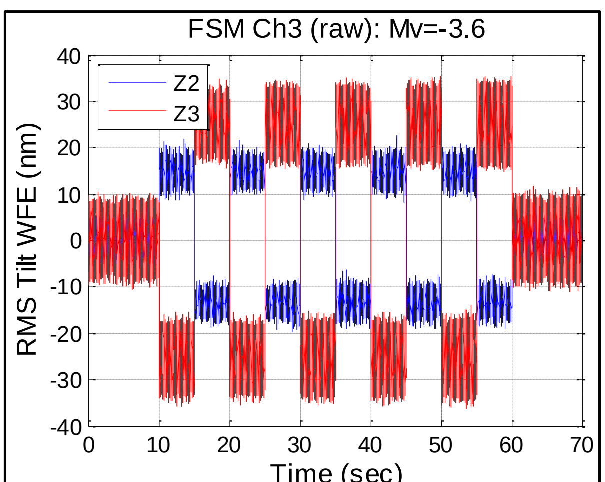
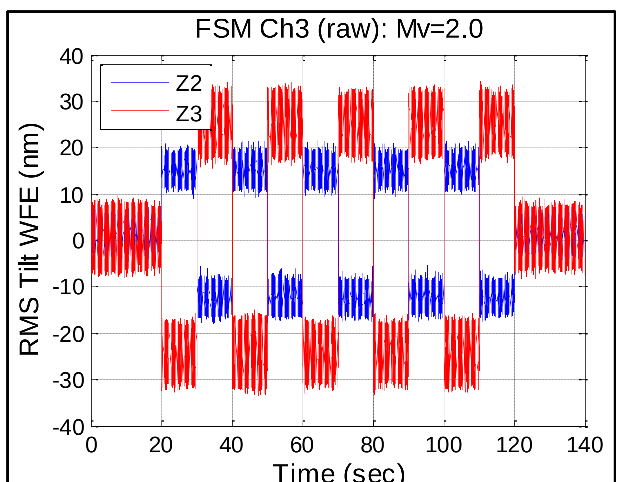
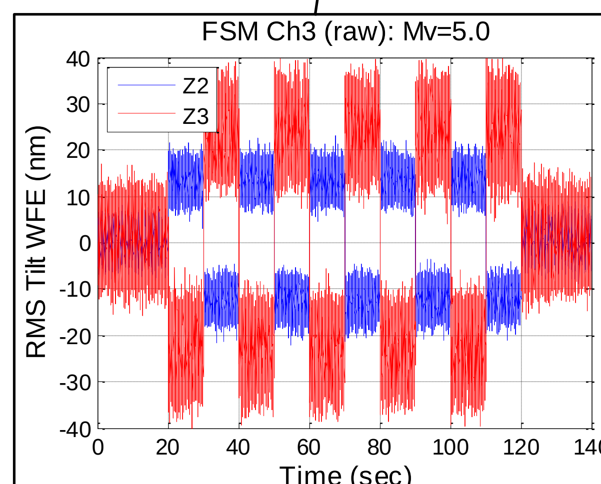
LOWFS Sensing Accuracy vs. Stellar Magnitude: Line-of-Sight (Z2 & Z3)

- Fixed voltage square wave command is applied to FSM actuators, creating a fixed tilt wave form (Ch3 data are plotted)
- LOWFS sensor measured the chopping amplitude are compared.
- **LOWFS tilt measurement remains fair constant through many orders of magnitude (10^4X) of source brightness.**



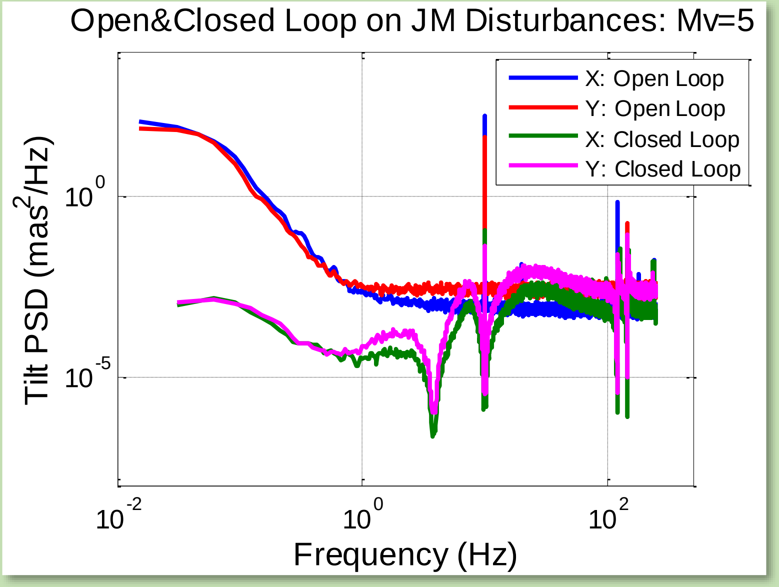


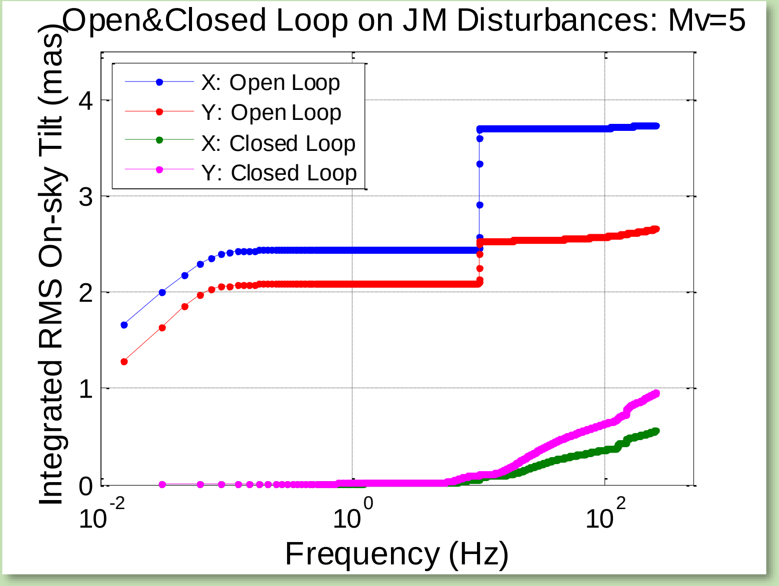




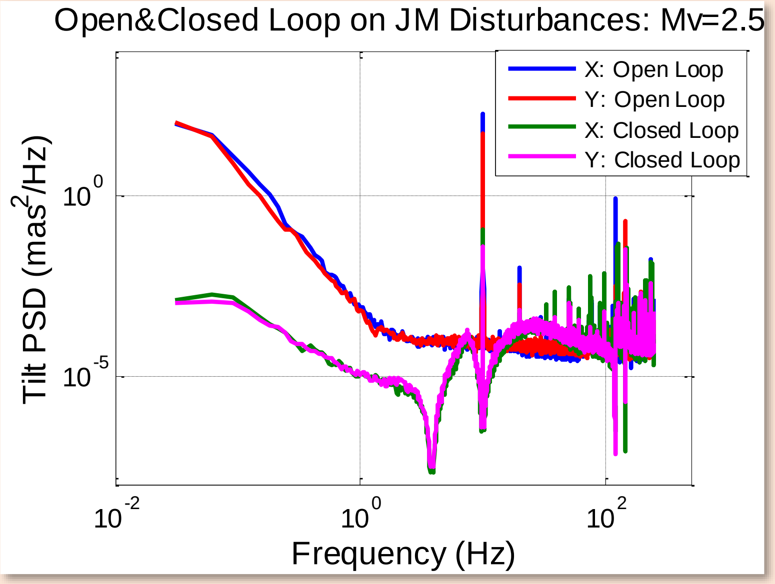
LOWFS/C LoS Performance

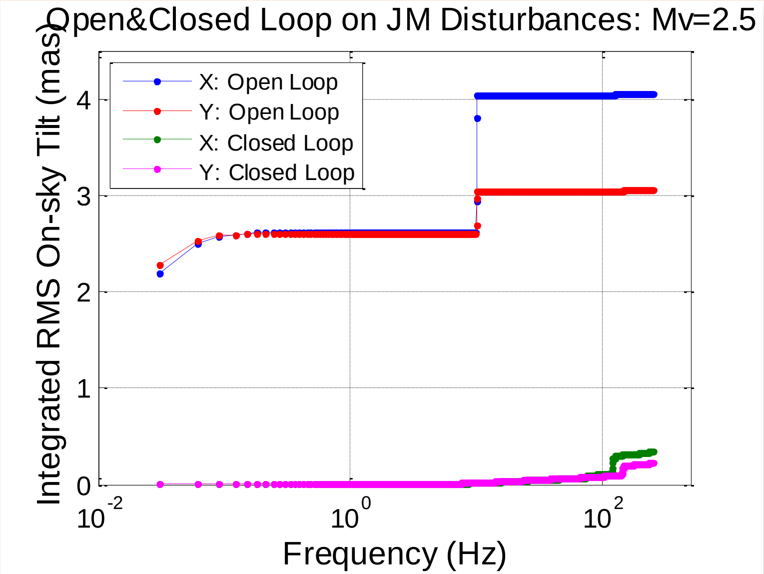
Performance on Mv = 5 Star



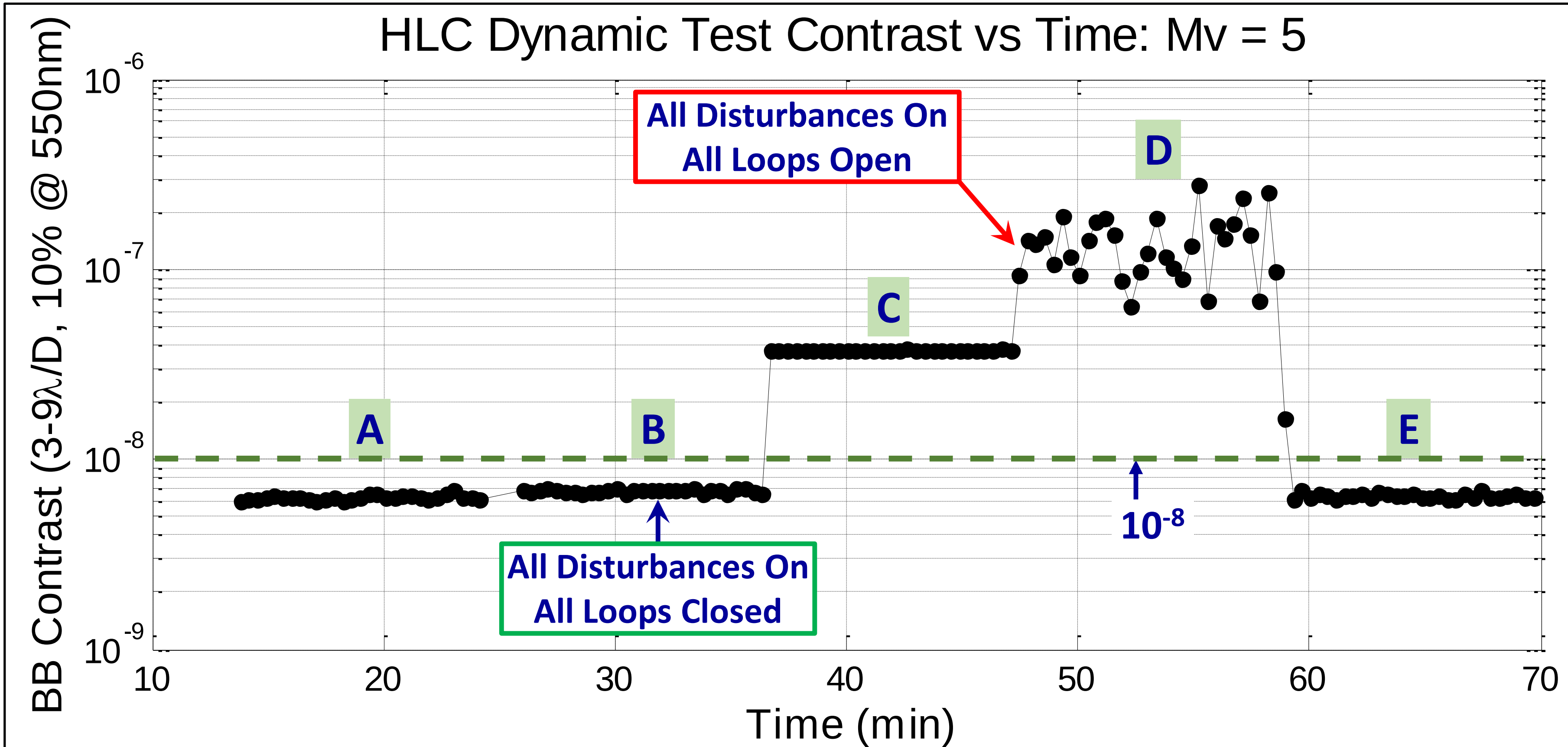


Performance on Mv = 2.5 Star





LOWFS/C LoS Dynamic Test for the Faint Star (Mv = 5.0)



Sequences of dynamic test (each ~10 min):

A. FB on & FF on with lab environment

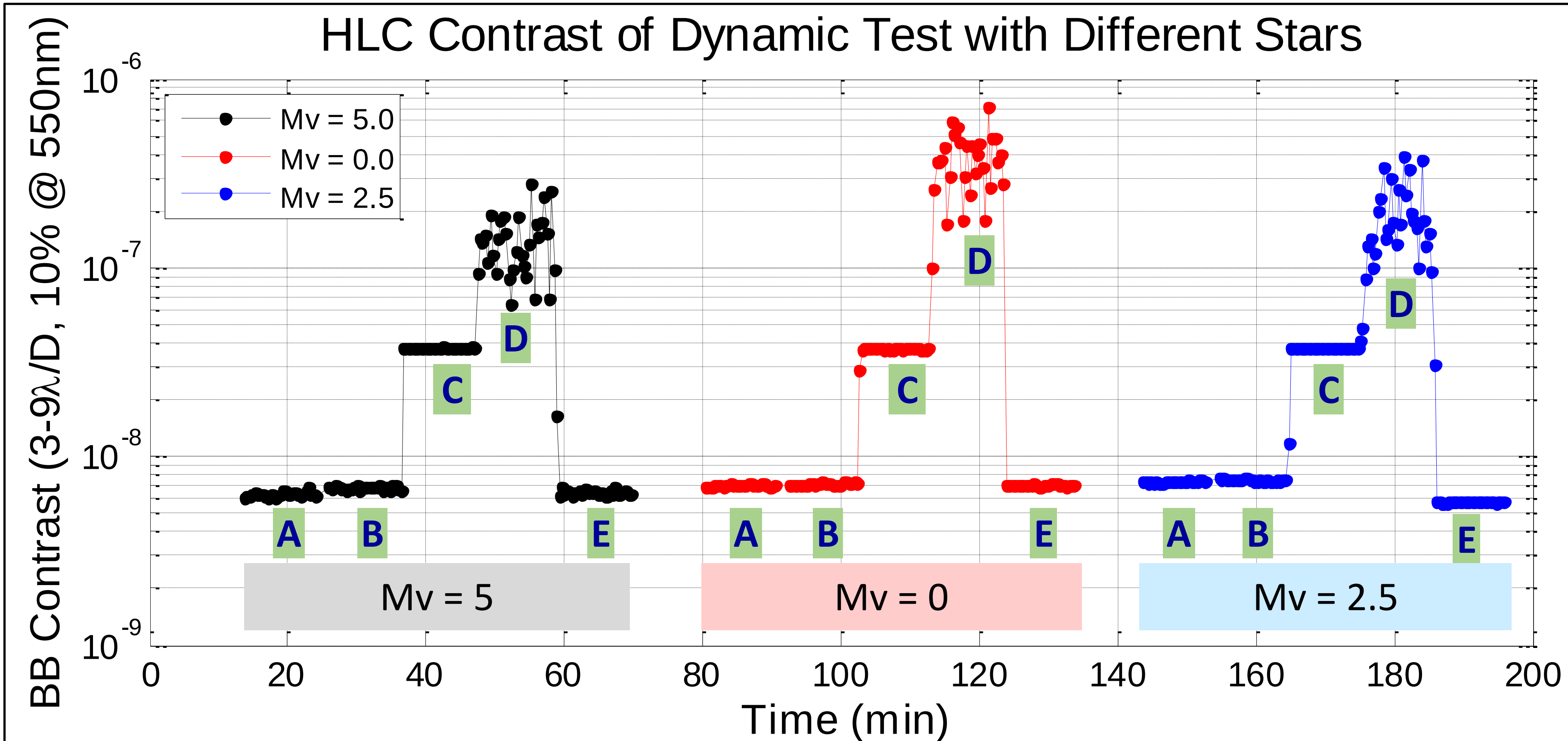
B. FB on & FF on with JM induced dynamics (ACS + RWA jitter at 600rpm)

C. FB on & FF off with JM induced dynamics (ACS + RWA jitter at 600rpm)

D. FB off & FF off with JM induced dynamics (ACS + RWA jitter at 600rpm)

E. FB on & FF on with lab environment

LOWFS/C LoS Dynamic Test with Different Stellar Magnitudes



Sequences with each stellar magnitude (Mv = 5.0, Mv = 0.0, Mv = 2.5):

A. FB on & FF on with lab environment

B. FB on & FF on with JM induced dynamics (ACS + RWA jitter at 600rpm)

C. FB on & FF off with JM induced dynamics (ACS + RWA jitter at 600rpm)

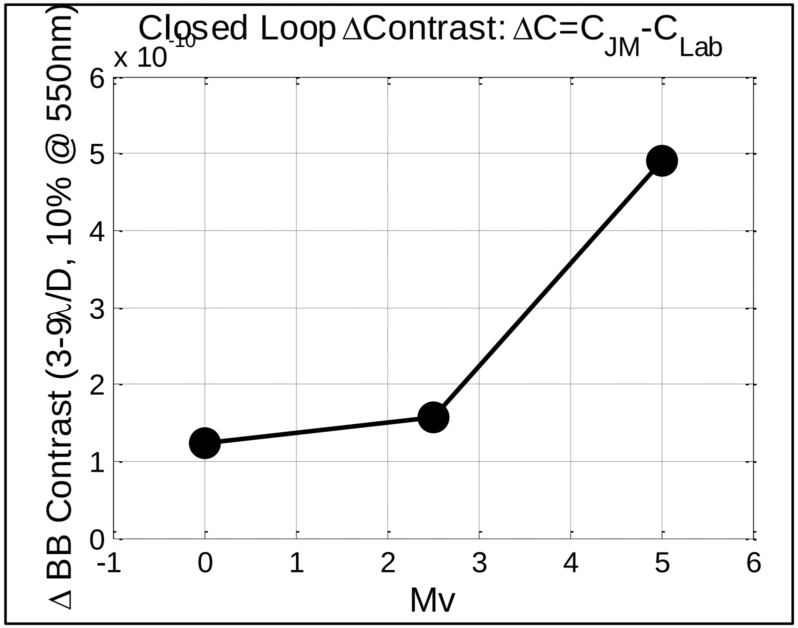
D. FB off & FF off with JM induced dynamics (ACS + RWA jitter at 600rpm)

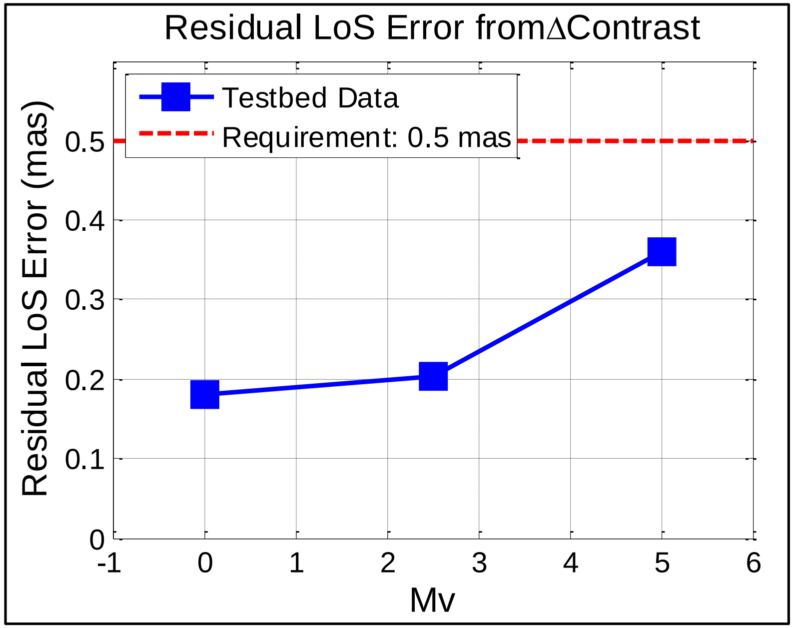
E. FB on & FF on with lab environment

Post LoS Correction Residual Error Calculated from ΔContrast

- Delta contrast (ΔC) between the closed loop at lab environment (quiet) and JM disturbances ($\Delta C = C_{JM} - C_{lab}$)shows the effectiveness of LOWFS/C LoS loop suppression of JM induced WFIRST like LoS disturbances.
  - In previous plots Mean of B – Mean of A
- Fainter star has more contribution of contrast degradation due to the larger LOWFS sensing error (upper right plot)
- Using HLC jitter sensitivity we can calculate the post correction residual LoS error
- Convert ΔC to LoS residual error:
  - Use contrast sensitivity from testbed: 1.89e-9 ΔC / mas² (3-9 λ/D) per axis

- **The results (≤0.36) met the requirement of 0.5 mas residual even at fainter star (Mv=5)**





LOWFS Sensing Accuracy vs. Stellar Magnitude: Focus (Z4)

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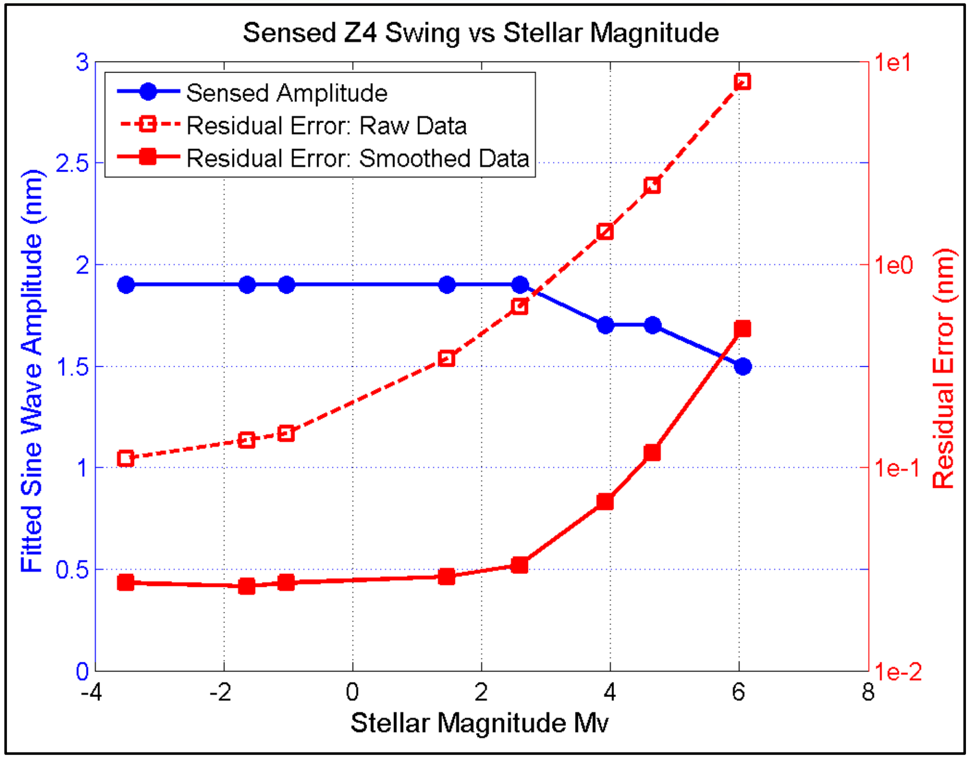
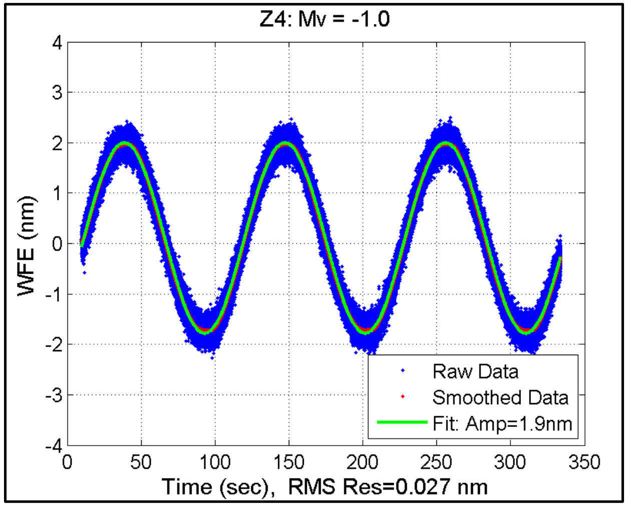
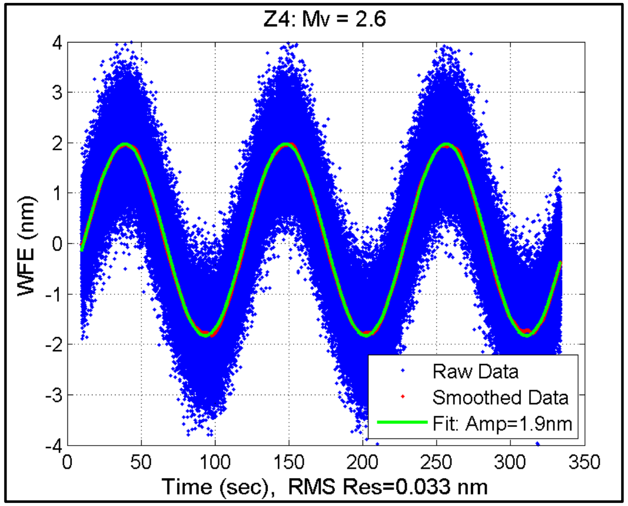
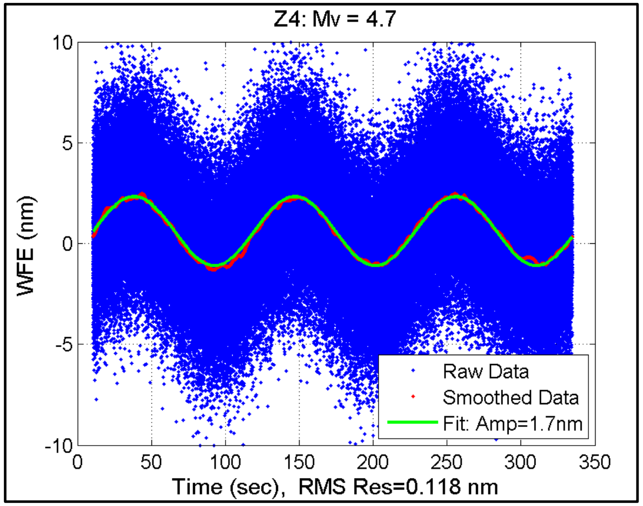
- Testbed source focus position is driven in sinusoidal fashion, creating sinusoidal focus swing of about +/-2 nm.
- LOWFS sensor measured focus and other low order modes.
- **LOWFS focus measurement (smoothed or fitted) remains fair constant through many orders of magnitude (10^4X) of source brightness**



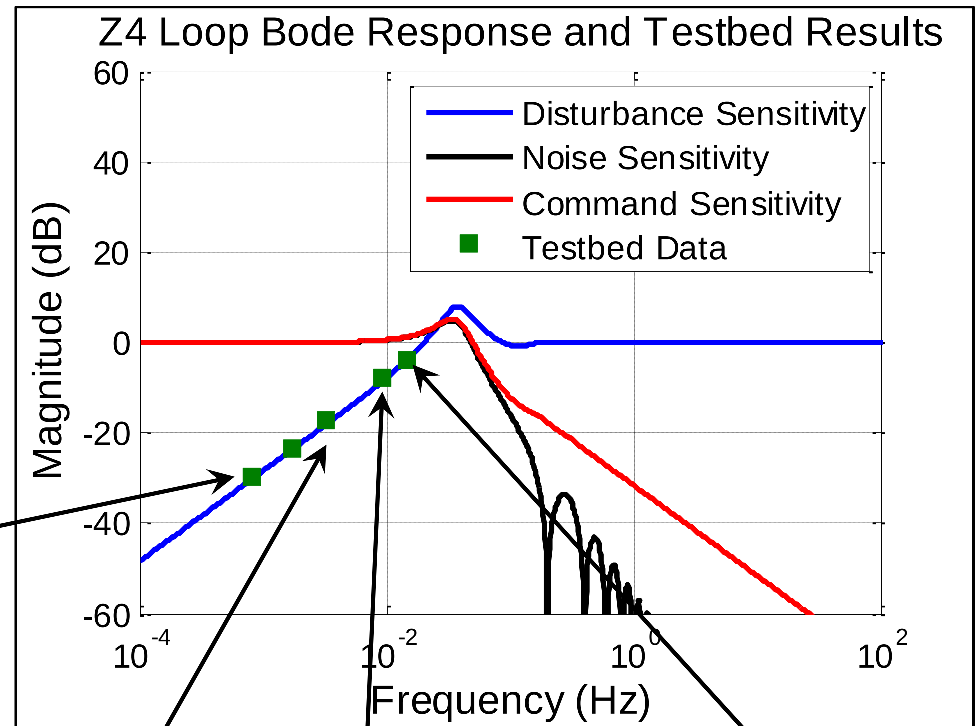


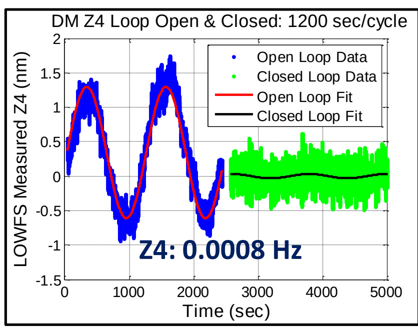


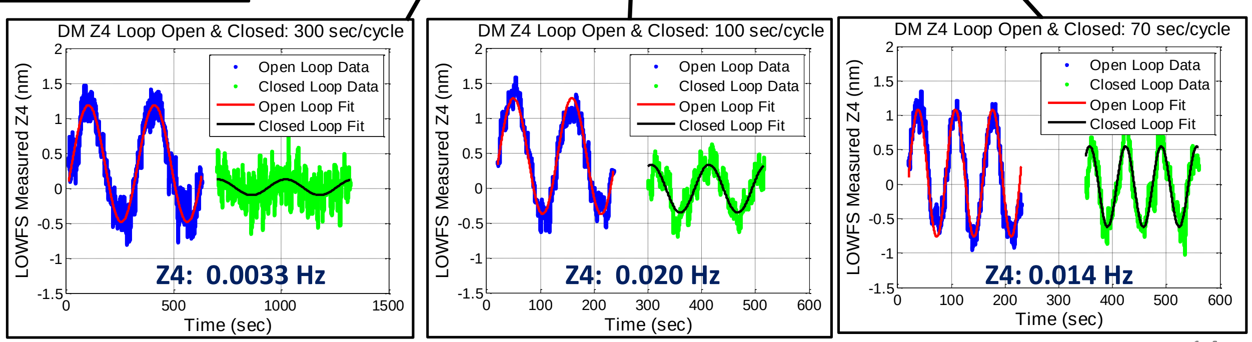


LOWFS/C DM Loop Performance: Data vs. Model

- **Focus drift generated by OTA simulator**
  - ±2 nm swing sinusoidal focus disturbance
  - 4X larger than expected in WFIRST flight
- **DM is used to correct focus (Z4)**
- **Solid blue line is the model prediction and green squares are testbed data**
- **Open (blue) and closed loop (green) LOWFS Z4 measurement at various frequencies are plotted in the sub-panels.**







- **Excellent agreement between model and TB measured DM loop performance**

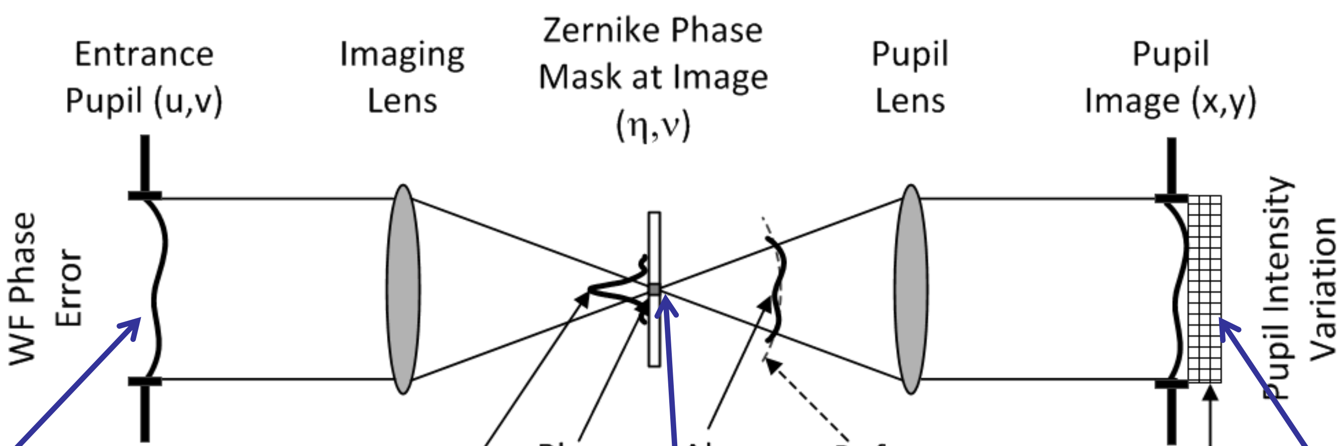
Conclusions and Future Work

- LOWFS/C performance has been tested using source brightness equivalent to stars in the flight like condition (Mv ≤ 5.0).
- With WFIRST like line-of-sight jitter injected by the testbed's Jitter Mirror the LOWFS/C can maintain the contrast stability for source as faint as Mv = 5. The post correction residual jitter, measured by coronagraph contrast, has shown to meet the WFIRST jitter requirement of 0.5 mas.
- Using source equivalent to Mv = 5 the testbed measured focus error rejection matches model prediction very well for LOWFS/C low order (focus) correction loop using a DM.
- We have also demonstrated simultaneous starlight light suppression wavefront control (EFC) while LOWFS/C is correcting the injected WFIRST like line-of-sight and wavefront disturbances, which will be reported in the next talk.
- Future work on the testbed for LOWFS/C:
  - Integrating an existing integral field spectrometer (IFS) to the OMC testbed to demonstrate CGI spectroscopy mode working with LOWFS/C under dynamic condition.
  - Updating OTA-Simulator which includes updated jitter mirror and pinhole relay optics which will provide more capability of dynamic wavefront test
  - New CGI mask designs

Backup Slides

Zernike Wavefront Sensor Concept

- **Zernike WFS (ZWFS) measures wavefront error (WFE) from interference between the PSF light passing through inside and outside the phase dimple (diameter ~ λ/D) placing at the PSF core**
  - Same principle as Zernike phase contrast microscope
  - <u>With phase dimple at phase shift of π/2, pupil image intensity variation is proportional to the WFE: $\Delta I \sim \pm 2\varphi$</u>
- **WFIRST CGI LOWFS uses linearized differential image to sense the delta WFE**
  - Rejected starlight from ~3 λ/D focal plane mask cause the ZWFS can only measure low order WFE
  - LOWFS camera samples pupil at 32x32 pixels with 20% band light to improve ZWFS' SNR
- ***ZWFS converts pupil phase error into intensity variation on the LOWFS camera***



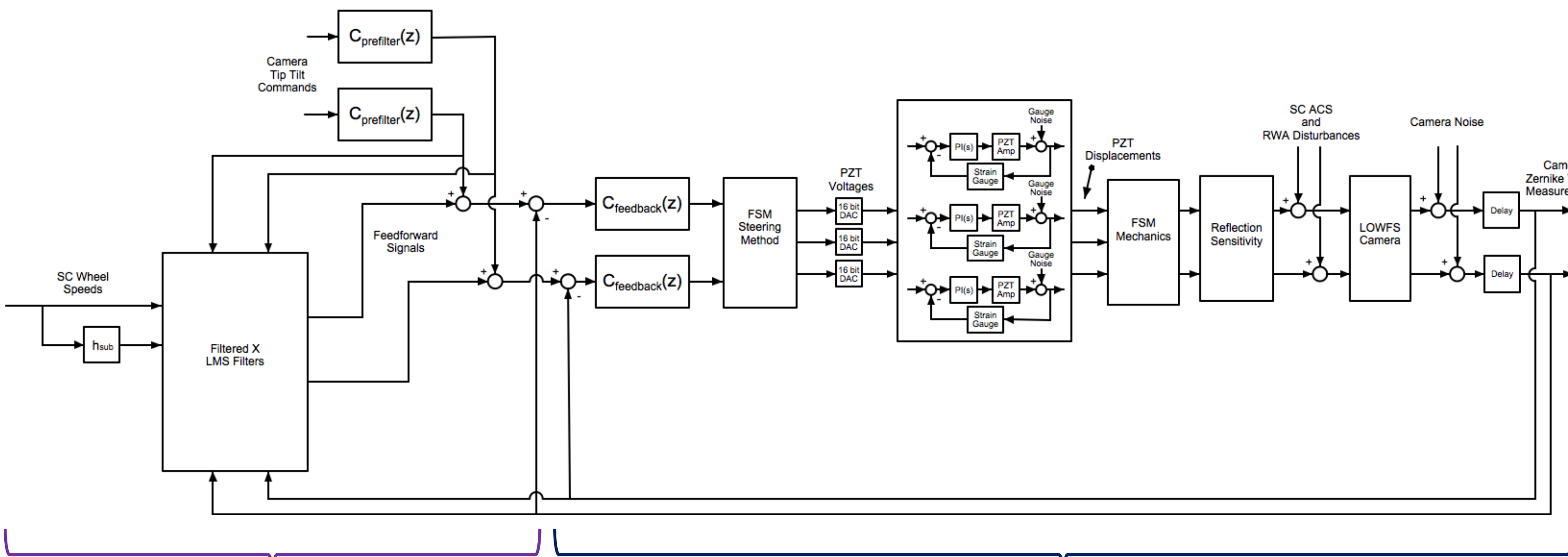
$$E(u,v) = P(u,v)\cdot A(1+\varepsilon(u,v))e^{i\varphi(u,v)}$$

$$I = A^2\left(1 + 2\varphi(x,y) + \varepsilon(x,y)^2 + \varphi^2\right)$$

$$\hat{E}(\eta,\upsilon) = A\cdot CPSF(\eta,\upsilon)e^{i\theta} + A\cdot CPSF(\eta,\upsilon)\otimes F\{\varepsilon(u,v) + i\varphi(u,v)\}$$

WFIRST LOWFS/C Line-of-Sight Control

- **Line-of-sight control uses both feedback and feedforward loops**
- **Feedback path to cancel slow ACS LoS drift**
  - LOS loop is shaped for **optimal rejection of the ACS disturbance and LOWFS/C sensor noise.** This is done by balancing the error contribution from camera noise and LoS drift from ACS
- **Feedforward path to cancel high frequency tonal LoS jitter from reaction wheels**
  - RWA speed information is used to determine the disturbance frequencies
  - A least-mean-square (LMS) filter estimates the gain and phase of the tonal disturbances
  - Correction commands are directly sent to FSM



LoS Feedforward **LoS Feedback Loop**